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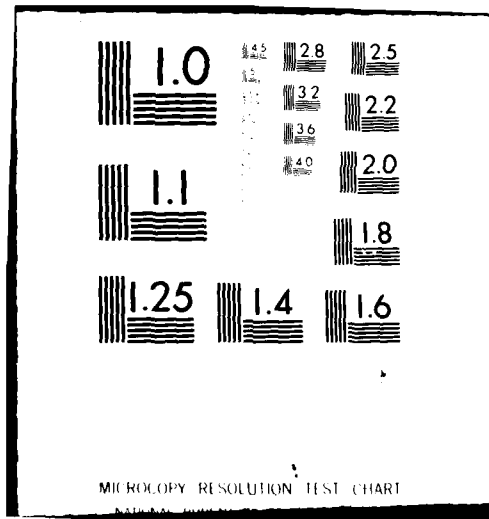
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FOUNTAIN-JET TURBULENCE

By

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ABSTRACT

A series of experiments was conducted on a model to
investigate the characteristics of fountain jets that
develop beneath hovering VSTOL aircraft. The results con-
firm the results of previous studies in that normally
developing fountains possess abnormally high turbulence
levels that can be reduced by the presence of trip devices
placed along the fountain stagnation line. The present work
shows that fountain turbulence is highly anisotropic with
the intensity of the streamwise component an order of
magnitude greater than the cross component. Further, the
anamoly appears to occur only in fountains produced by jets
of air that strike normal to the ground surface; jets that
strike at angles other than the perpendicular do not appear
to generate highly turbulent fountains.

INTRODUCTION

The flow field in the immediate vicinity of a VSTOL aircraft hovering in ground proximity can be divided into six more or less distinct regions (Figure 1). Of particular interest here are Regions 1, 2, 3, and 5, i.e., those regions wherein the flow causes forces and moments to be induced upon the airframe. The induced forces are usually divided into two parts for convenience. The first, "suck-down", is a negative (thrust degrading) force caused by the fact that the turbulent, high-speed jets beneath the air-craft planform entrain considerable quantities of ambient air that induce lower-than-ambient static pressures on the planform under-surface. The other force, which is positive (thrust enhancing), is usually referred to as "fountain buoyancy." It can occur when the aircraft exhaust con-figuration consists of more than one jet so that upward moving jets, or fountain jets, are produced (Region 3); the pressure recovery that results from fountain jet/planform impingement produces an upward component of lift. Since the magnitude of both suckdown and fountain buoyancy are con-figuration dependent, they often represent significant percentages of total engine thrust.

A number of anomalies in the basic behavior of fountain jets as compared with the behavior of other turbulent free jets have been observed. When the subject of VSTOL ground effects was first exposed to study, a reasonable simplifica-tion in experiments appeared to be the use of image planes for geometrically symmetric flows. However, the results of such tests were quite different than those obtained from complete jet models (References 1 and 2). An explanation was obtained by Adarkar and Hall (Reference 3) who observed that fountain jets decayed much more rapidly than jets produced on image planes. A subsequent investigation of the characteristics of fountains produced by the impaction of two plane jets flowing along a ground plane was made by Kind and Suthanthiran (Reference 4); they observed that, although the fountains so produced had local velocity distributions similar to that of a two-dimensional free jet, the fountains differed in that both the spreading rate, the associated decay rate, and the longitudinal turbulent intensities were about three times higher than those usually observed in free jets. Witze (Reference 5) encountered similar spreading rate anomalies in his work with fountains produced by circu-lar jets after ground impacts; those fountains had spreading rates between 2 and 3 times higher than expected from free-jet results. Hill et al., (Reference 6) in work with foun-tain jets impacting fuselage models, detected an oscillatory behavior in fountain-jet locations, whereas Foley (Reference 7), in an experiment with two-dimensional fountains, ob-
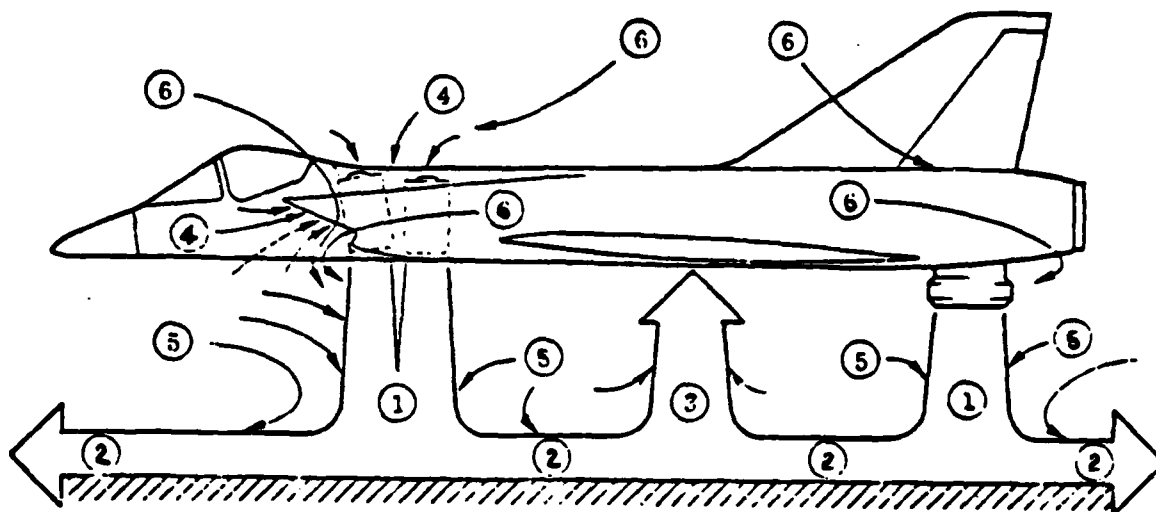
1 EXHAUST FLOW (FREE JET)

2 GROUND JET

3 FOUNTAIN JET

4 ENGINE INLET FLOW

5 & 6 ENTRAINED AMBIENT AIR

Figure 1 Flow Field Near a Hovering VTOL Aircraft

served that the insertion of a trip wire on the ground plane at the stagnation line produced a fountain jet whose spreading rate was much smaller than that of a usual fountain; in fact, the fountain with the trip wire produced a jet whose spreading rate was about the same as a normal two-dimensional free jet. (This may provide some explanation of the results of References 8 and 9 wherein small grids placed on ground planes produced major changes in the flow fields.)

Foley speculated that the high spreading rates, turbulence levels, and decay rates were possibly due to oscillation of the stagnation zone and large scale turbulence in the fountain.

An experimental investigation of fountain jet velocities and turbulence levels was conducted to delineate the origins of the turbulent anomalies associated with fountain jets by extending the previous studies. The results are presented herein.

EXPERIMENT

A. Test Facility

The test program was conducted at the General Dynamics' Fort Worth Division Ground Effect Test Facility with a 1 m by 1 m ground plane. Two nozzles 4 cm in diameter, D, were mounted 46 cm apart and 41 cm above a ground plane. Figure 2 shows a representation of the test flow field. In addition, the ground board could be fitted with three trips - a 0.32-cm square rod, a 2.54-cm high plate, and a rod 0.32 cm in diameter - along the mean stagnation line. The ground plane could be tilted to vary ϕ so that STOL jet/ground plane angles as well as VTOL ($\phi = 90$ degrees) could be simulated. Air was supplied by the plant service air system. Although nozzle pressure ratio (NPR) could be varied, it was determined early on that NPR had little effect on the results of interest. Therefore, NPR was set at 2.0 for all data reported herein.

B. Data Acquisition Equipment

Fountain jet velocities were detected with a Thermal Systems Inc. Model 1050 dual-channel constant-temperature anemometer equipped with a Thermal Systems Inc. Model 1232 AF miniature hot-film cross probe. The probe was mounted on a remotely-actuated surveying arm so that h, x, and θ could be varied at will. The probe was calibrated in a DISA calibration wind tunnel at the beginning of each test day
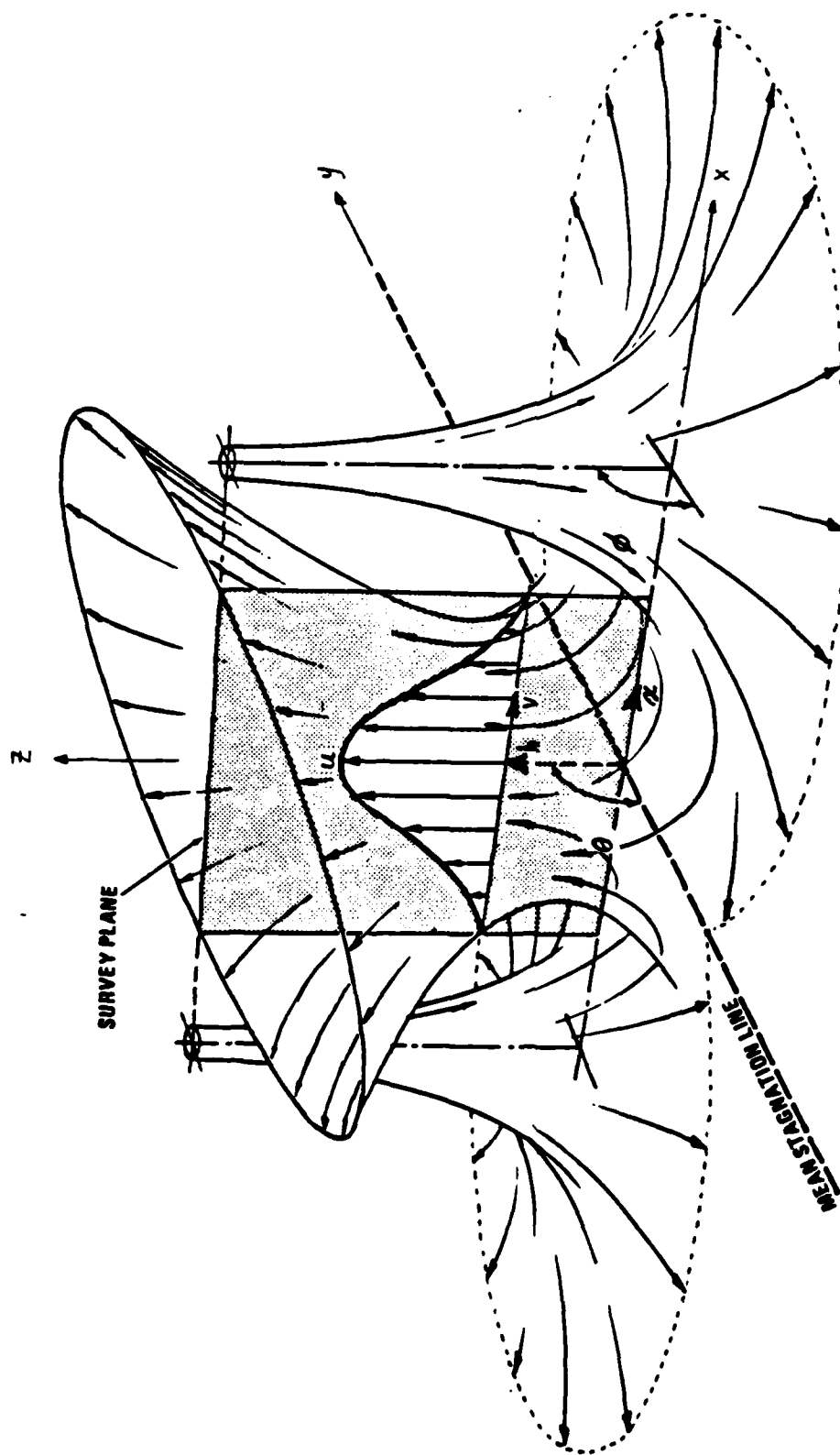
Figure 2. Fountain Jet Geometries

and was recalibrated twice each test day to check for drift.
Turbulent intensities were measured with a Systron Donner
Model 7003 true RMS voltmeter; spectral measurements were
obtained with a Spectral Dynamics model SD2001 DM spectrum
analysis system.

Cross-correlations were obtained at two locations: (1)
between two Thermal Systems Inc. Model 1264 sub-miniature
conical hot-film sensors, one mounted in the ground plane
(Figure 3 (B)) and one in the fountain flow (A), and (2)
between probe (A) and a Kulite pressure transducer flush-
mounted at the nominal stagnation point (C).

RESULTS

A.   VTOL Conditions (ϕ = 90 degrees)

The measurements of the mean velocities U, both with
and without trips in place, confirmed the results of Ref-
erence 7 (Figure 4). The 0.32-cm trips, which were sized to
be about the height of the virtual boundary layer of the jet
flowing along the ground plane at the stagnation line, in-
creased peak velocity by 1/3; the cross-section shape of the
trip made little difference. The 2.54-cm trip increased
peak velocity by 3/4. It was sized to be of approximately
the same as the virtual height of the ground flows at the
stagnation line. The effect on the jet spread rates must be
inferred because the presence of downward flows from the
nozzles limited the range of surveys in the x-direction.
Nonetheless, from momentum considerations, it seems reason-
able to speculate that the trips decreased the fountain
spreading rate. From a practical aspect, these results
would indicate that a VSTOL aircraft should be careful about
hovering over an irregular gound surface because of the
possibility of encountering sudden changes of fountain
buoyancy. When the data are plotted in non-dimensional
form, that is, velocities normalized by centerline veloci-
ties and x by fountain jet half-widths, the shape factor is
influenced neither by the trips nor by altitude (Figure 5).

The present results showed that the turbulent inten-
sities were greatly decreased by the presence of a trip
(Figure 6). Further, as can be seen by the power spectra
shown on Figure 7, this decrease is predominate at the lower
end of the spectrum where the larger-scale eddies are
present. There is a fair amount of anisotropy in the un-
tripped case with the streamwise intensity $(u'/u)^2$ an order
of magnitude higher than the intensity in the x-direction
$(v'/u)^2$. It must be mentioned that, especially at the in-
tensity levels in the untripped flows, the hot-film probe
used in the experiments was beyond its range of dependable
accuracy. Although the exact numerical values of intensity
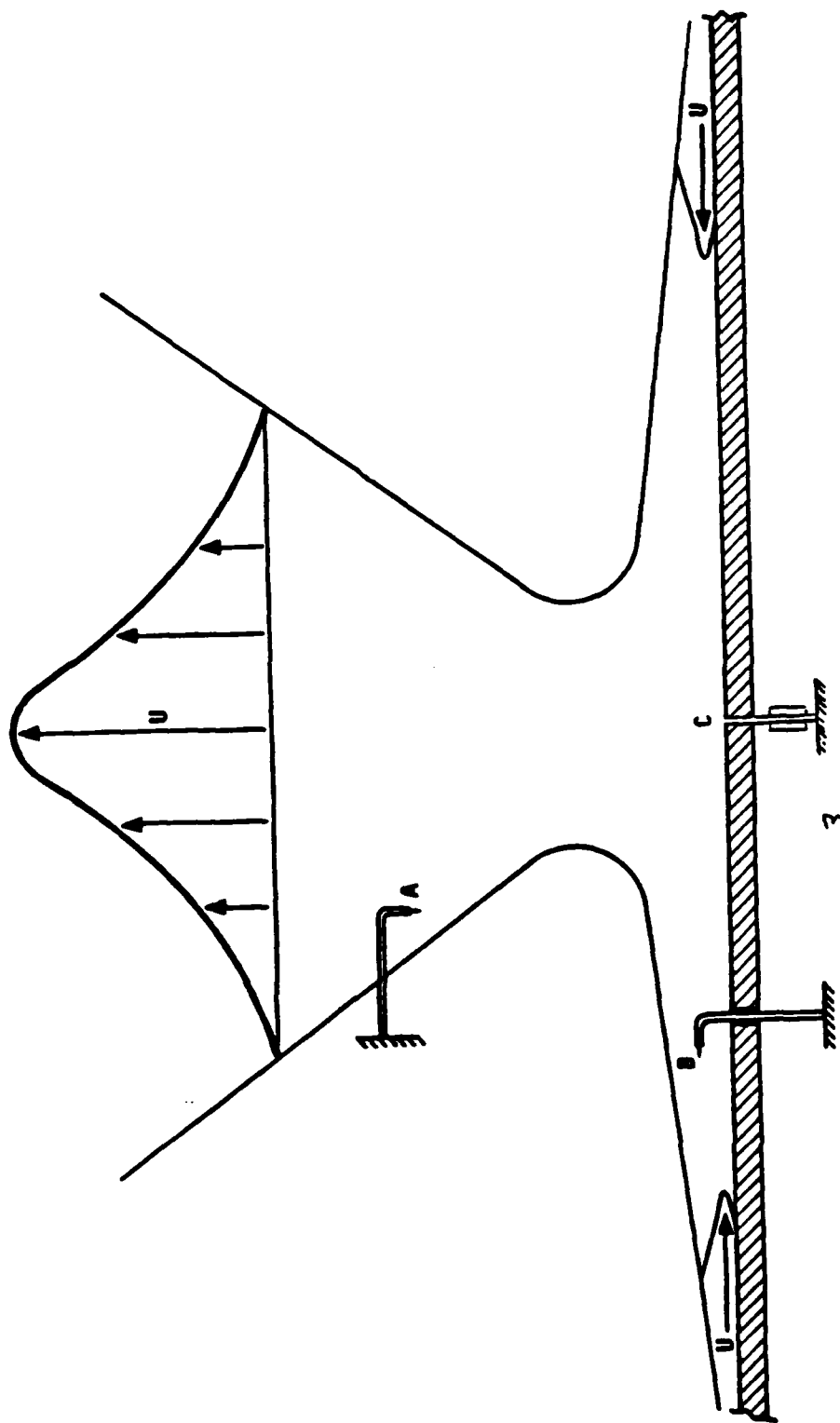
Figure 3 & 4 Fountain Jet Cross-Section
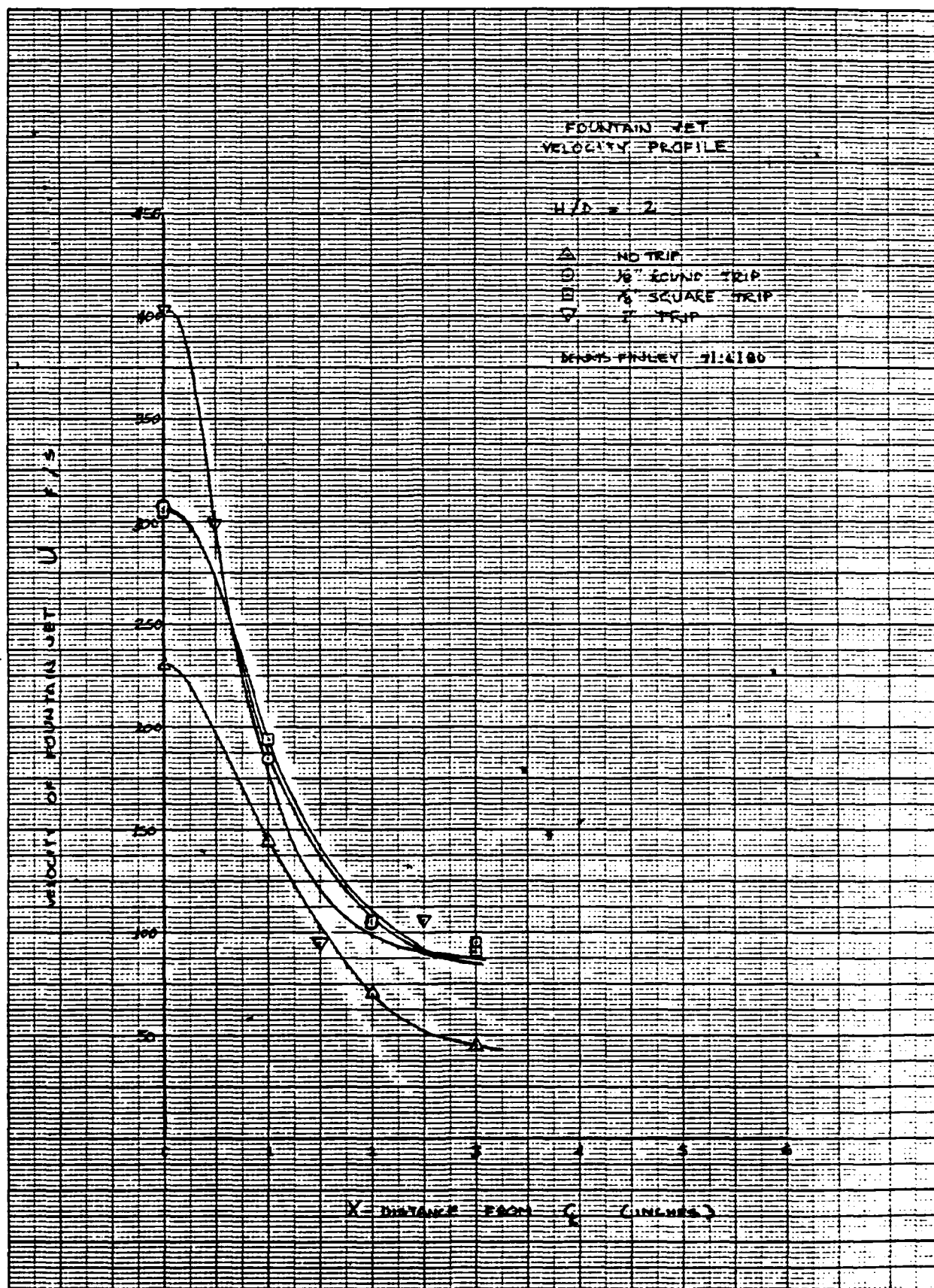
Figure 4. Fountain Jet Velocity Profile

Figure 8, Fountain Jet Shape factor vs Non-Dimensional distance from G. S.

Figure 16 Tripped and Untripped Turbulent Intensities

$$\left(\frac{u'}{U}\right)^2$$
$$\left(\frac{v'}{U}\right)^2$$

H/D = 2

$\phi = 0°$

TURBULENT INTENSITIES $\left(\frac{u'}{U}\right)^2, \left(\frac{v'}{U}\right)^2$

UNSTRIPPED
$X = 2''$

FREQUENCY (HZ)

0   100   200   300   400
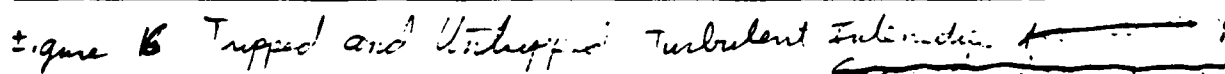
1-INCH TRIP
$X = 2\frac{1}{2}''$
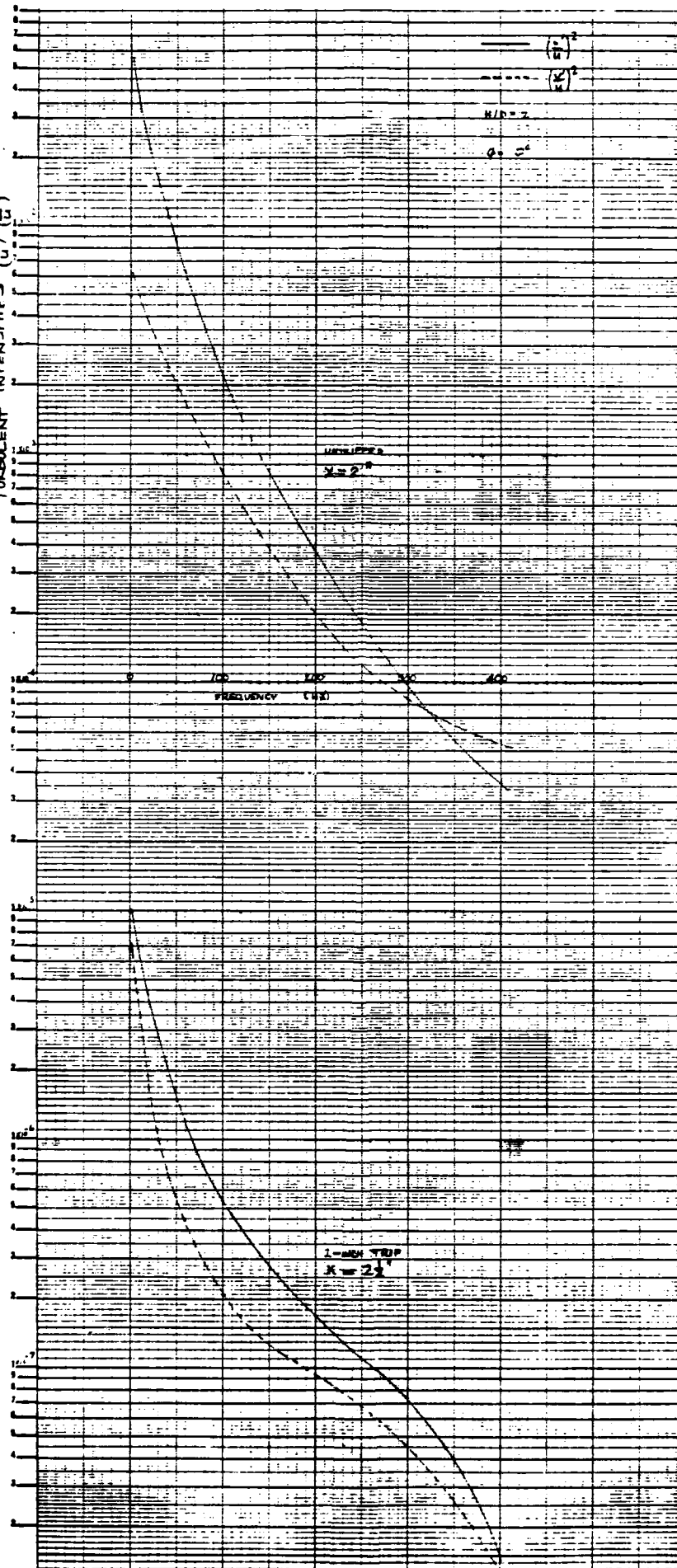
Figure 7. Turbulent
Intensity, ...
... $\phi = \pm \mathbb{I}$ ...

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K•E 10 X 10 TO ... CENTIMETER 18 X ?? CM
KEUFFEL & ESSE... CO MADE IN U.S.A.

16-1   18-6

2   4   6

H/D ═══ ═════ ── ──

X = 6/E

NO TRIP

DATA FROM HOT WIRE
ANEMOMETER

CROSS CORRELATION

TIME DIFFERENCE — SEC — K 10⁻⁹

-20   -10   0   10   20   30   40

Figure 8 Untripped Fountain Jet

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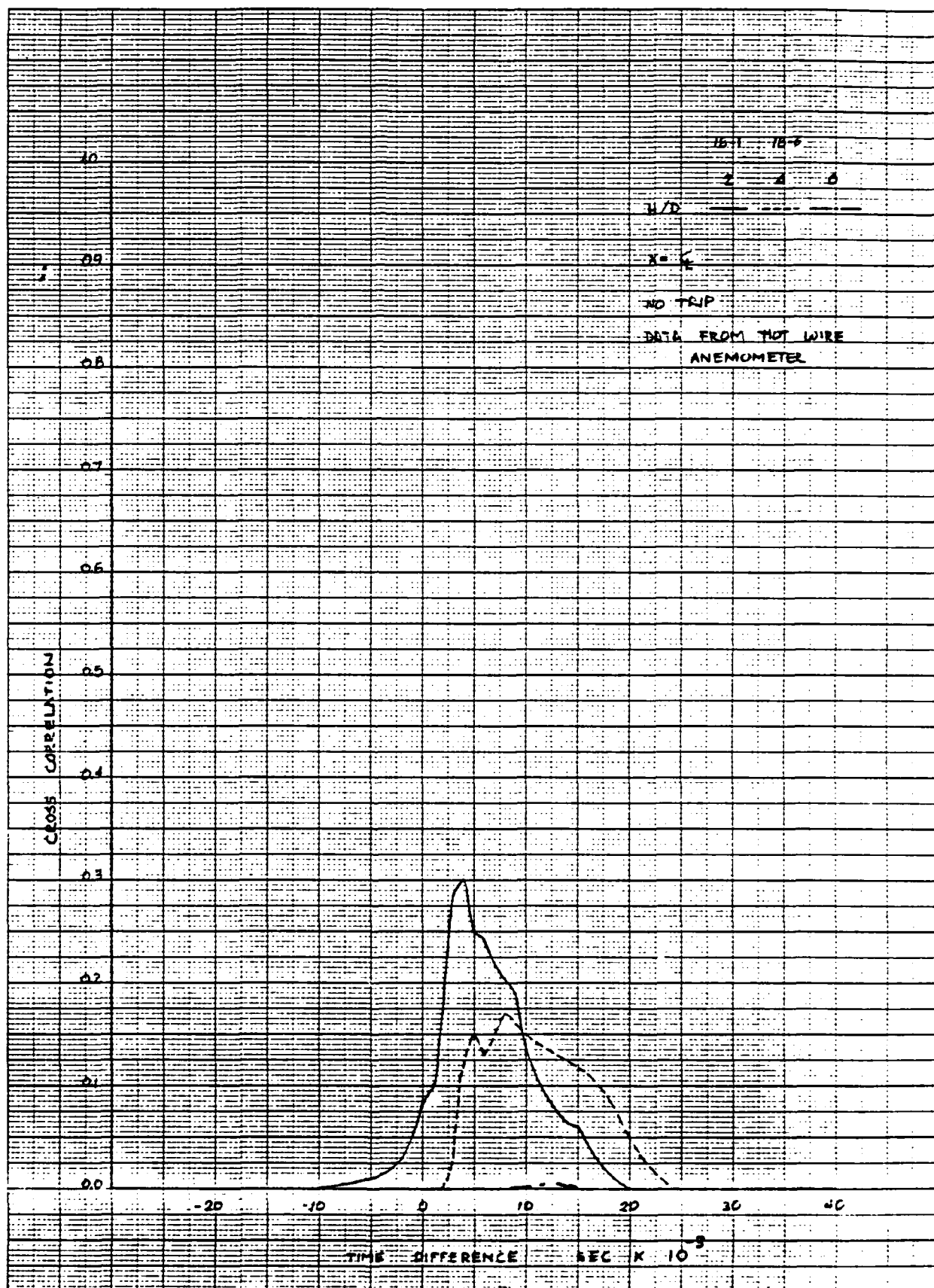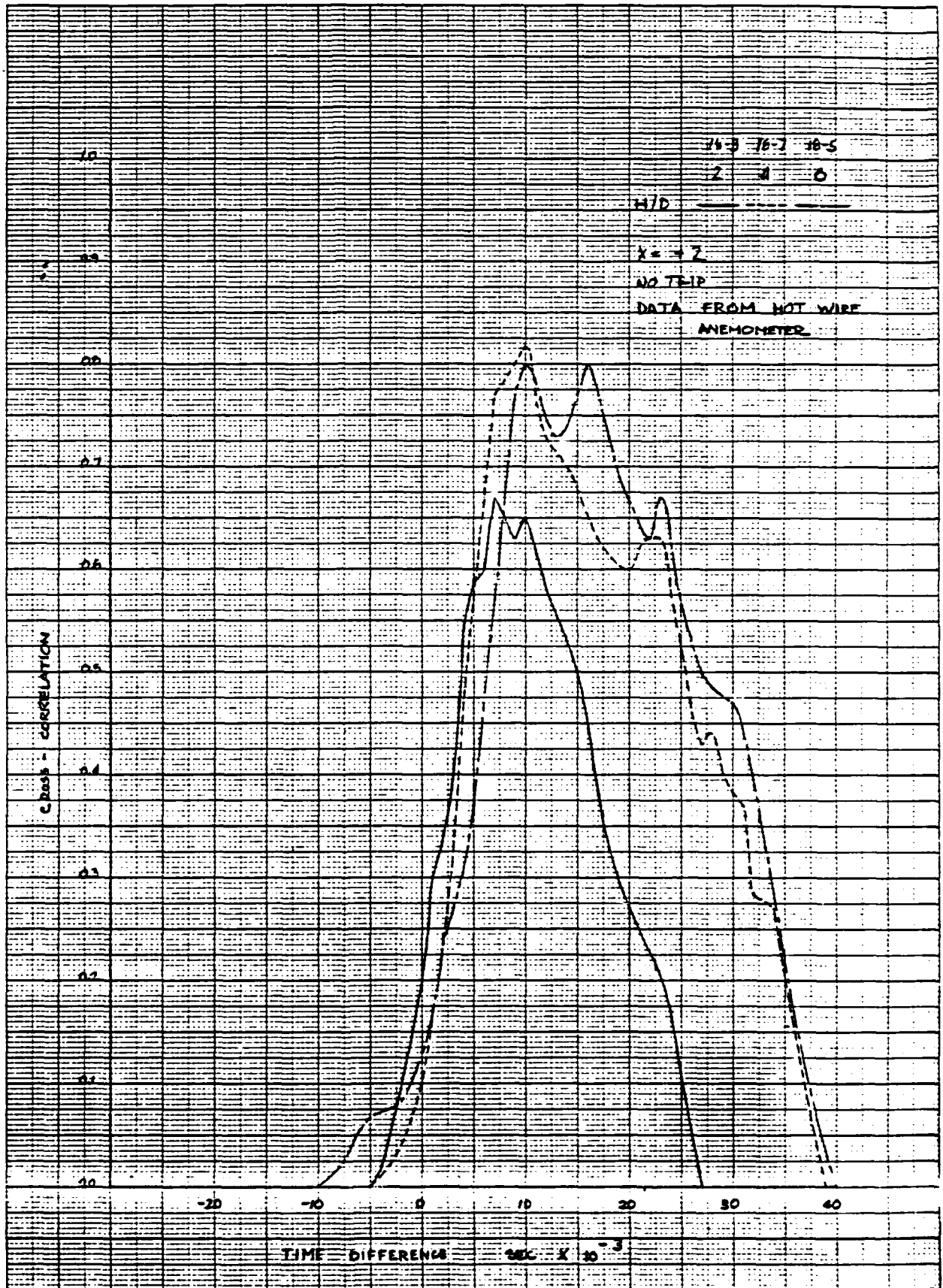
F16. 9.

shown are somewhat suspect, it is felt that the trends shown
are valid. A more appropriate split-film probe was con-
sidered, but the idea was discarded because the fragility of
the probe was incompatable with the flow environment.

The hot-film data show that, in the flow with the 2.54
cm trip in place, there was virtually no correlation between
the turbulence in the ground jet and that in the fountain.
However, in the untripped case, the opposite was observed.
Figure 8 displays the correlation where the fountain probe
altitude varied at the centerline; the probe in Figure 9 was
positioned at x = 5.08 cm or in the fountain jet wing. It
can be seen that the correlations are highly persistant and
by far the strongest in the area of the greatest turbulent
intensity; the correlation on the centerline rapidly decays.
On both figures, the times to the peaks are consistant with
the flow times for a particle to traverse the distance
between the two probes. The correlations between the
pressure transducer mounted on the stagnation line and the
hot-film probe in the fountain showed similar trends.

Surveys made at θ = 60 degrees and 30 degrees showed
that the effectiveness of the trip diminished somewhat, but
that the general results observed at θ = 90 degrees remained
the same.

B. STOL Case ($\phi \neq$ 90 degrees)

A surprising result was produced by inclining the
nozzles to the ground plane. The fountain anamolies of high
turbulence, etc., completely dissappeared with deflections
of as little as 15 degrees from the vertical. As can be
seen on Figures 10 and 11, insertion of the trip has almost
no difference in either the mean velocities or in the
turbulence levels.

CONCLUSIONS AND RECOMMENDATIONS

The previously observed high turbulence levels in
fountain jets has been reconfirmed. The present data would
indicate that, in the vicinity of the stagnation line on the
ground plane, there is a strong turbulence amplification
mechanism, which seems to act at all frequency levels but
which has its most dramatic influence in amplifying the
larger turbulent eddies. Previous speculation that the
mechanism consisted of a oscillation of the stagnation line
which gave rise to a fountain whose flow undulated is not
consistant with the present data. Had this speculation been
correct, the fountain centerline correlations would have
persisted with altitude to the same extent as those in the
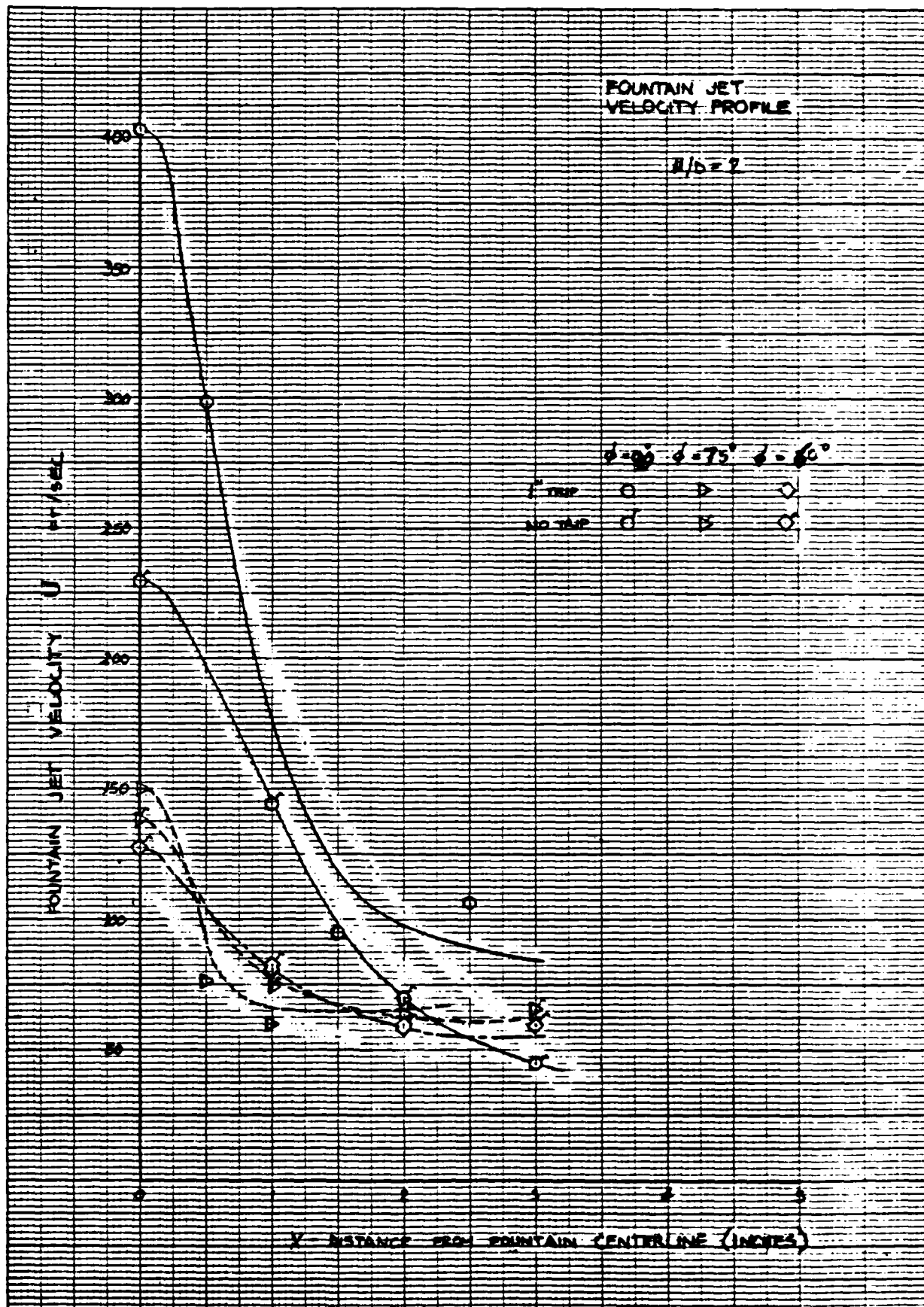
Figure 18. Fountain Jet Velocities for Varying Ground Heights

$u/o = 2$

$\phi = 80°$

$\left[\dfrac{u'}{u}\right]$

$\left[\dfrac{v'}{u}\right]$

0.20

0.15

0.10

0.05

X DISTANCE FROM ₵ (INCHES)

TRIP   NO TRIP
○ u'/u   ○ u'/u
□ v'/u   □ v'/u

FIGURE 11

fountain wings; the data, of course, showed otherwise. Nonetheless, certain of the data seem consistant with the undulation speculation, in particular, the anisotropy of fountain turbulence with extra strong amplification of the s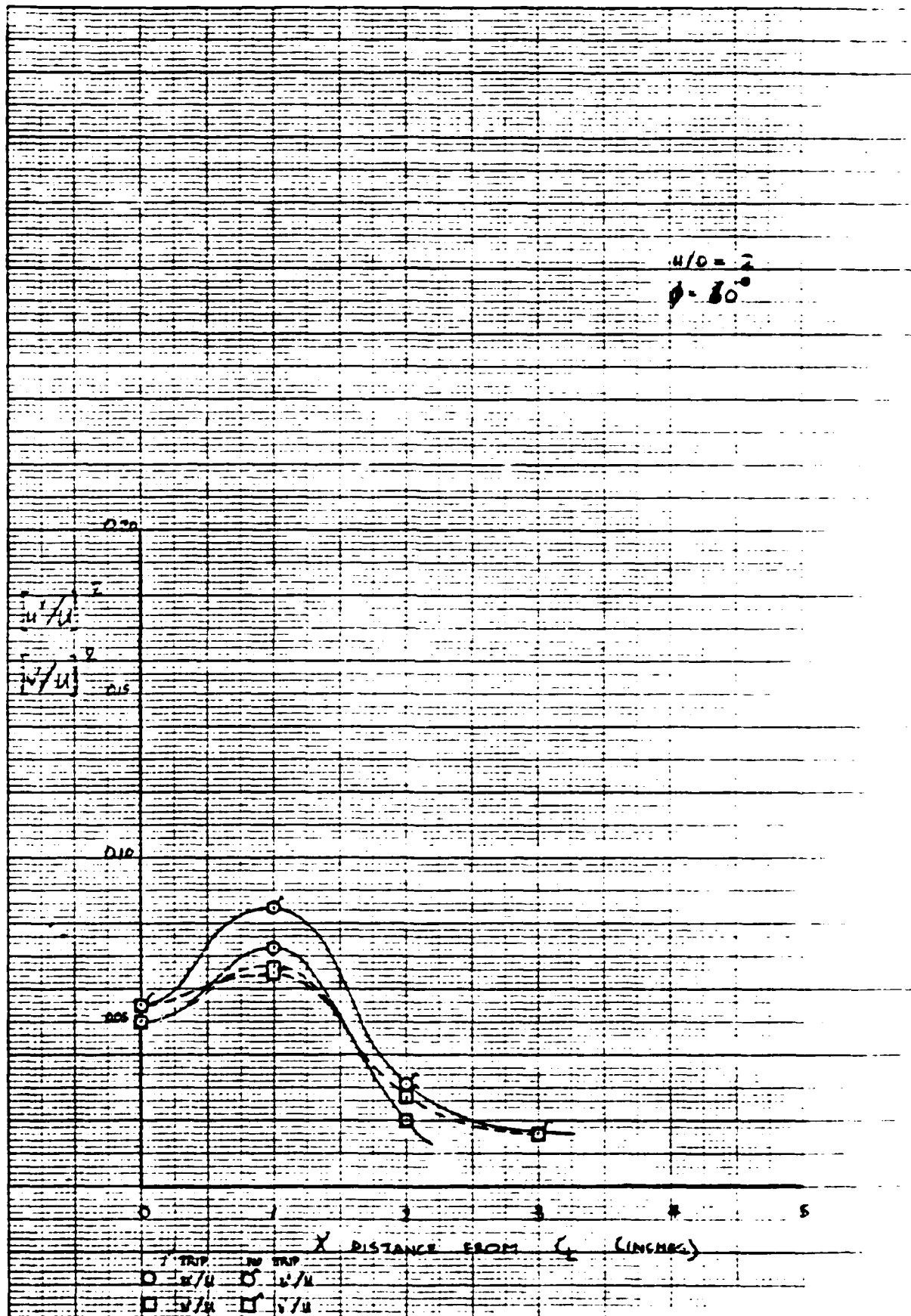treamwise component. There seems, however, to be little doubt that the amplification does take place within the stagnation line region because of the effect of even small trips on the fountain flow.

The measurements made at ϕ = 90 degrees, $\theta \neq$ 90 degrees seems contradictory to those at $\phi \neq$ 90 degrees. In both cases, the fountain flows developed from ground jets that did not impact head-on but rather at an angle. However, in the former case, the strongest part of the fountain developed from jets that did impact normally, and, thus, the turbulence amplification that resulted may well have propogated down the stagnation line, whereas, in the latter case, it did not.

The present experiment, in all, has confirmed some aspects of fountain jet behavior only to raise further questions of the underlying physics involved. It is the authors' opinion that further investigation into the physics is required. While the present work was done with flow velocities appropriate for aircraft engines, it is felt that future investigations should be conducted at much lower, laminar conditions so that controlled disturbances could be introduced into the ground flows and the stagnation process studied in detail both by anemometry instrumentation and, possibly, flow visualization.

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VELOCITY PROFILES

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